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A multi-criteria decision aid methodology to design electric vehicles public charging networks

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This article presents a new multi-criteria decision aid methodology, dynamic-PROMETHEE, here used to design electric vehicle charging networks. In applying this methodology to a Portuguese city, results suggest that it is effective in designing electric vehicle charging networks, generating time and policy based scenarios, considering offer and demand and the city's urban structure. Dynamic-PROMETHE adds to the already known PROMETHEE's characteristics other useful features, such as decision memory over time, versatility and adaptability. The case study, used here to present the dynamic-PROMETHEE, served as inspiration and base to create this new methodology. It can be used to model different problems and scenarios that may present similar requirement characteristics. [http://dx.doi.org/10.1063/1.4921087]

INTRODUCTION

Transports are nowadays mainly dependent on fossil fuels, implying large greenhouse gas emissions (Chapman, 2007). However, electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) are emerging as an alternative to mobility needs.

The EV requires a completely different refueling system from the one for internal combustion engines vehicles (ICEV). Not only the refueling time is much higher but the autonomy will be much lower which consequently implies more refueling cycles. Predictably some electric vehicle users will charge their vehicles at home whenever they own a private garage. On the other hand others will have to use public car parking, being important to assure that the most suitable locations are made available for charging stations or points, especially in urban areas and these identified forehand. This process could be a chicken-and-egg dilemma, when identifying what comes first: the charging network or the EV users (Mak *et al.*, 2013). Undeniably, EV users must not be conditioned by the lack of an adequate EV charging network in their normal routes.

Around the world, in most major cities, charging stations for EVs are being implemented as the adoption of this alternative transport becomes more effective. The objective of this article is to present a new methodology that was developed first to assist on the design of electric vehicle charging networks, called dynamic-PROMETHE which is a dynamic multi-criteria decision aid methodology. The methodology is then applied to Angra do Heroísmo, a Portuguese city, capital of Terceira Island which is part of the Azores archipelago located in the Atlantic Ocean.

This case study serves as theme to present the dynamic-PROMETHEE methodology, as a possible application, although it's not limited to it. It also includes an example of a sensitivity analysis, representing different policy scenarios, that leads to conclude the robustness and versatility

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of the methodology. This new methodology, although developed initially for this purpose of identifying the best locations to implement public EV charging points, gives a new approach to the multi-criteria decision aid methods and therefore has a much broader application.

I. LITERATURE REVIEW

A. Electric vehicles

Several authors reviewed the state of the art of EVs (Chan, 2002; Green *et al.*, 2014; Helmers and Marx, 2012; Mak *et al.*, 2013; Pina *et al.*, 2014; Kempton and Letendre, 1997; Kempton and Tomić, 2005; Kim and Rahimi, 2014; and Sovacool and Hirsh, 2009, among others). These authors point EVs advantages over ICEV in energy use diversification, reduced oil imports and dependency, low noise and air pollutants emissions, increased energy efficiency, low operation and maintenance costs and possible contribution to the power grid balance. Nevertheless, the referred authors also state that these are not to be considered straightforward in replacing the ICEV, being the effect of EVs on greenhouse gas emissions dependent on the energy mix in the electricity generation, on the EV adoption rate and also on the EV users charging behavior, when considering the complete energy life cycle. Grid operation challenges, EV high investment costs, low autonomy and long charging times are also referred by the authors as a concern.

Nonetheless, the EV appears to present more advantages than disadvantages when compared to the ICEV. Electric mobility is a trend in development with the contribution of multidisciplinary teams constituted by EV manufacturers, battery developers, grid operators, urban planners and managers and other stakeholders, without forgetting users or early adopters.

B. Electric vehicles charging networks

The EV battery charging process can be done in two ways: normal and fast charging. Normal charging will be the most universal one, since it requires fewer changes in logistics (the power socket can be a regular 110/220 V socket and will have less impact on the power grid. The battery capacity of an EV is around 20kWh, considering a Li-ion battery (Roland Berger, 2009), and takes about 6 to 8 hours to fully charge, meaning that the battery charging will take place while the vehicle is parked preferably for longer periods of time.

If possible, users will charge their vehicles in their own private garages or parking spaces (Camus *et al.*, 2010). Nonetheless charging stations must be implemented in public parking spaces, mainly within the city limits, where cars are left the most and for longer periods of time, for those who don't have private garages and for those charging during the day, away from their residences. Therefore, urban areas must be provided with suitable charging networks (Gartner and Wheelock, 2009) in order to assure sufficient autonomy to EV users, to avoid autonomy concerns to limit the widespread of EVs use.

In the future, probably charging networks will comprise mainly slow charging stations (Gartner and Wheelock, 2009) as the widespread use of fast charging stations would increase power demand in the electrical grid (Mak *et al.*, 2013) adding larger difficulties to grid management.

The locations of these charging points are very important since they have to respond to future user's demand, taking into account technical constrains, such as limited installation sites at a given location or electrical grid limitations. Thus, when designing the electric charging network, the first question that arises is where charging points should be located. The importance of this problem has been discussed by some authors, among them van den Bossche *et al.* (2003) for the case of Brussels capital region. Authors like Electric Transportation Engineering Corporation (2009), James (2009) and Verdantix (2009) present a set of operational guidelines for electric mobility, including charging stations. While Hanabusa and Horiguchi (2011), Chen *et al.* (2013), Frade *et al.* (2011) and Gavranović *et al.* (2014) proposed a set of methodologies to design charging networks for EVs and PHEVs.

In 2009, the Portuguese government assigned charging networks to the main urban centers, without following any methodology, with the exception of Lisbon (Frade *et al.*, 2011 and Raposo, 2010). Since then, charging stations were deployed in the main urban areas in public parking areas.

The problem of designing an optimized EV charging network can be seen as a facility location problem where multiple criteria must be considered.

C. Infrastructure location problem

The study of infrastructure location problems, both static and deterministic, began in 1909 with Alfred Weber, where the author was concerned in determining how to site a warehouse in order to minimize the total distance between the warehouse and the several costumers (Owen and Daskin, 1998). Nevertheless, these problems can be extremely difficult to solve when multiple infrastructures are considered. One example of this is the hospital infrastructure layout problem, where several infrastructures must be sited in several locations (Hahn and Krarup, 2001). Another example is the infrastructure sitting of refueling stations (Wang and Lin, 2009), which main focus is the refueling pattern.

Due to particularities of the EV charging process, it is not that important to consider the distance between origin and destiny of the EV user or its possible path, as it is considered that an EV user can get to its destination (when doing normal daily trips). Thus, it becomes important to assess where EV users may park, rather than knowing the path that they take, since the objective is to establish the location and the number of charging stations. Zvi Drezner approached this problem by considering a known variant demand over time and a predetermined number of infrastructures to deploy (Drezner, 1995), which is not the case here. The main objective for this methodology is to create a tool that can aid decision making for facility location over a variable demand with time.

To solve the problem of identifying the locations and number of charging stations for EVs, a new methodology is developed, based on the PROMETHEE method for solving multi-criteria decision making problems (Brans *et al.*, 1986) and applied for solving the location and number of charging points for EVs at Angra do Heroísmo.

D. Multi-criteria decision making

Decision making or decision aid is an area of research aimed at supporting decision makers who are faced with numerous and conflicting evaluations, comprising multiple criteria. These must then be combined in an appropriate method and trade-off amongst them is needed (Sousa and Kaymak, 2002). It is the processes that results in the selection of a decision among several alternatives.

The subjects under evaluation during the decision process define the set of alternatives A:

$$A = \{a_1, a_2, a_3, \ldots, a_n\} \tag{1}$$

The different alternatives are compared using a set of criteria G:

$$G = \{g_1(a_i), g_2(a_i), \ldots, g_k(a_i)\} \quad a_i \in A \tag{2}$$

For each criterion, the preference structure is defined, whether the criterion should be maximized or minimized, as follows:

$$\begin{cases} \forall\, l : g_j(a_i) \geq g_j(a_l) \\ \exists\, l : g_j(a_i) > g_j(a_l) \end{cases} \quad \Leftrightarrow \quad a_i P a_l \tag{3}$$

$$\forall\, l : g_j(a_i) = g_j(a_l) \quad \Leftrightarrow \quad a_i I a_l \tag{4}$$

$$\begin{cases} \exists\, l : g_j(a_i) > g_j(a_l) \\ \exists\, m : g_m(a_i) < g_m(a_l) \end{cases} \quad \Leftrightarrow \quad a_i R a_l \tag{5}$$

Where P, I and R stands for preference, indifference and incomparability, respectively. In other words, an alternative is preferable to another if it dominates it. Two alternatives are indifferent if the criteria values are the same. Two alternatives are incomparable if one is better in one criterion and the other better in another criterion, so it is impossible to decide which is best.

Having defined a set A of alternatives and a consistent set of criteria G on A, the decision-maker aims to:

- determine a subset of alternatives considered to be the best with respect to the set of criteria (choice problem),

- divide A into subsets according to some norms (sorting problem), or
- rank the alternatives of A from best to worst (outranking problem).

The outranking problems have the advantage of being able to rank all the alternatives and therefore the decision-maker is able to get a better point of view or comparison between alternatives (Vincke, 1992).

In order to build the appropriate multi-criteria outranking method, some requisites have to be considered, as explained in the following (Brans and Mareschal, 2005):

1. The amplitude of the deviations between criterion evaluations of the alternatives is taken into account:

$$d_j\left(a_i,a_l\right) = g_j\left(a_i\right) - g_j\left(a_l\right) \tag{6}$$

2. Since the criteria $g_j\left(a_i\right)$ are expressed in their own specific units, the scaling effect is completely eliminated. It is not expected to come to decisions for proposed problems based on conclusions dependent on the scales in which the criteria are expressed.
3. In the case of pair wise comparisons, an appropriate multi-criteria method should provide information as: a_i is preferred to a_l; a_i and a_l are indifferent; a_i and a_l are incomparable. The objective is to reduce as much as possible the number of incomparable alternatives.
4. Different multi-criteria methods request additional information and operate using different calculation procedures so the proposed solutions can be different. In this way, methods that are understandable by decision-makers are preferable. "Black box" methods are not so advisable on this matter. That way a clear path to the solution is better understood.
5. In the same matter, an appropriate procedure should not include technical parameters that have no significance to the decision-maker.
6. Most methods allocate weights of relative importance to each criterion. These weights reflect a major part of the intelligence (and subjectiveness) of the decision-maker and it is not easy or straight-forward to fix them.

The methodology followed in this work, for solving multi-criteria outranking problems is the PROMETHEE method (Brans *et al.*, 1986). This has become a popular method with research work developed in several topics, namely: environment management, hydrology and water management, business and financial management, chemistry, logistics and transportation, manufacturing and assembly, energy management, and other topics that include several fields: medicine, agriculture, education, design, government, and sports (Behzadian *et al.*, 2009).

This method has been applied for solving multi-criteria decision aid problems, including location decision problems, such as: locating waste electrical and electronic equipment recycling plants is Spain (Queiruga *et al.*, 2008); locating a waste treatment facility in Finland (Hokkanen and Salminen, 1997); ranking enterprises according to an achieved level of business efficiency (Babic and Plazibat, 1998); planning a theme park in Madrid (Fernández and Martin, 1999); prioritize environmental projects in Jordan (Al-Rashdan *et al.*, 1998); find the most suitable underground ore transport system for a chromate mine in Turkey (Elevli and Demirci, 2004).

E. PROMETHEE

For a given multi-criteria problem with a set A of n alternatives that have to be compared using a set G of k criteria, the PROMETHEE method starts by comparing each pair of alternatives in A for all criteria in G by evaluating a set of $n \times k$ differences matrixes D_j, according to formula 6. The larger the deviation, the larger the preference.

For each criterion j in G it is necessary to define a preference function F_j:

$$P_j\left(a_i,a_l\right) = F_j\left[d_j\left(a_i,a_l\right)\right] \quad \forall\left(a_i,a_l\right) \in A \tag{7}$$

Which is defined between 0 and 1. This functions normalizes the differences values, eliminating all scale effects from the different criteria considered.

The preference function can be defined in various ways (Brans and Mareschal, 2005). In this work, the v-shape function is used for all criteria, which can be defined as:

$$P(d) = \begin{cases} 0 & d \leq q \\ \dfrac{d-q}{p-q} & q \leq d \leq p \\ 1 & d > p \end{cases} \tag{8}$$

Where q is the threshold of indifference, which is the largest deviation, considered as negligible by the decision maker and p is the threshold of strict preference, which is the smallest deviation considered sufficient to generate a full preference by the decision-maker

After evaluating the preference function for all criteria, it is necessary to aggregate the preference indices. Considering $a_i, a_l \in A$, the aggregation is defined as:

$$\pi(a_i, a_l) = \sum_{j=1}^{k} P_j(a_i, a_l) w_j \tag{9}$$

Where w_j is the weight of relative importance given to criterion j in G. These weights represent the importance of each criterion in the overall evaluation and they are dependent on the expertise of the decision maker, in respect with the following:

$$\sum_{j=1}^{k} w_j = 1 \tag{10}$$

In this way, if $\pi(a_i, a_l) \approx 0$ it implies that there is a weak preference of a_i over a_l while if $\pi(a_i, a_l) \approx 1$ it implies that there is a strong global preference of a_i over a_l. Taking into account that each alternative a_i is compared to the other $(n-1)$ alternatives, two outranking flows are defined: the positive outranking flow:

$$\phi^{+}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a, x) \tag{11}$$

and the negative outranking flow:

$$\phi^{-}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x, a) \tag{12}$$

The positive outranking flow shows how an alternative outranks all others. It shows its relevance character: the higher it is, the better the alternative. The negative outranking flow shows how an alternative is outranked by others. It shows its weakness character: the lower it is, the better the alternative.

The PROMETHEE II variant of the PROMETHEE method, eliminates all incomparabilities by the evaluation of the net outranking flow:

$$\phi(a_i) = \phi^{+}(a_i) - \phi^{-}(a_i) \quad a_i \in A \tag{13}$$

The ranking of the alternatives is given by the net outranking flow, where the alternative with the highest value is considered as the best alternative by the evaluation process. The rest of the alternatives are ranked accordingly, from the highest to the lowest net outranking flow.

Summarizing, the preference structure of PROMETHEE is based on comparing alternatives two by two, for each criterion, being the larger the deviation, the larger the preference. These values are normalized by preference functions, and, therefore, these preferences can be considered as real numbers between 0 and 1, annulling scale effects. Figure 1 presents the outranking basis of the PROMETHEE II method.

Using this approach, we obtain a rank of the best location to implement a given facility, in this case it would be a charging point. In the next section, we define a specific variation to the PROMETHEE II method in order to define the location of multiple charging points.

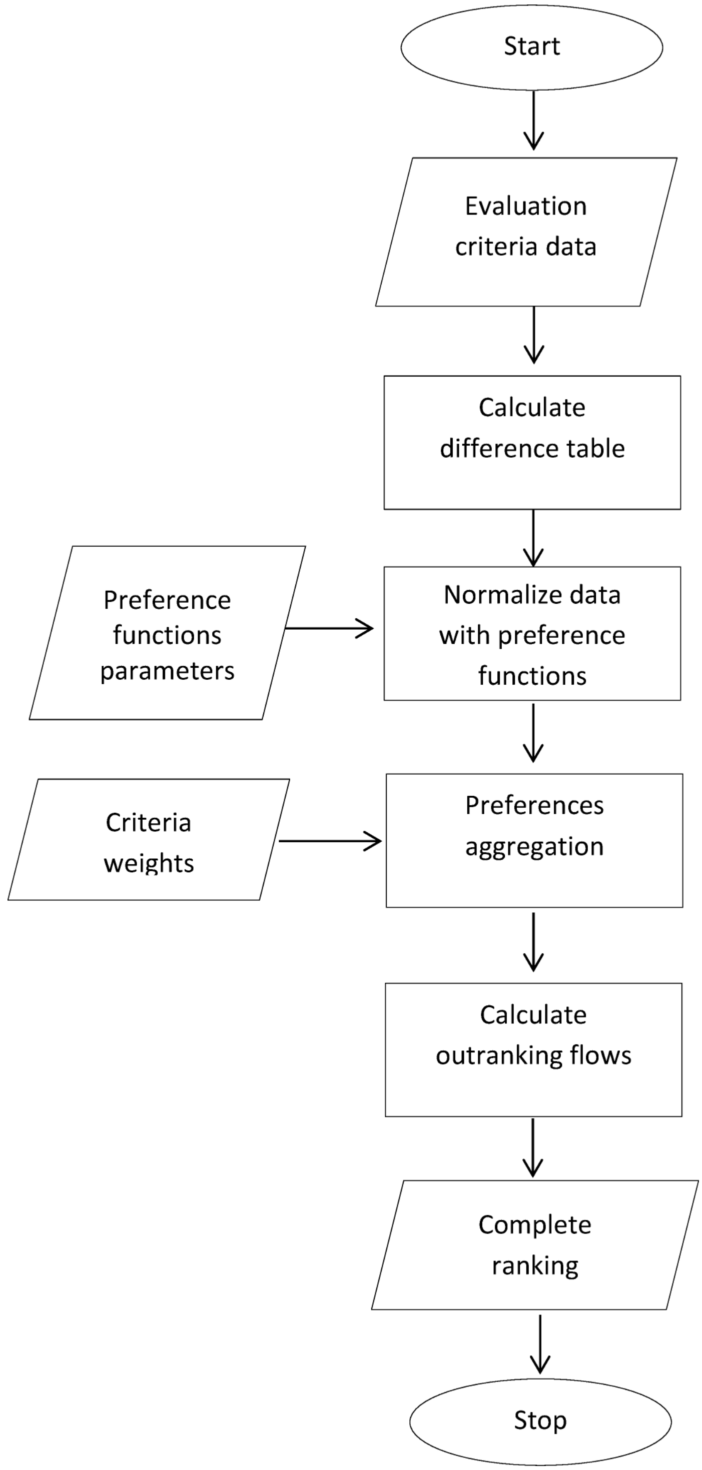

FIG. 1. **PROMETHEE II**.

II. METHODOLOGY

A. The charging point facility location

The decision process to deploy charging points for EVs uses a set of defined alternatives evaluated according to a series of conflicting criteria. For the design of a charging network, we define that the alternatives are the places or areas that are being considered to install the charging points, such as streets, neighborhoods or even cities. In this way, this approach can be used at different scales.

The criteria try to interpret the habits and needs for future users of EVs, based on actual habits and needs. Hence, this is considered a multi-criteria decision problem. The PROMETHEE algorithm follows a sequence of calculations with the objective of ranking the alternatives considering different objectives to be maximized or minimized, translated in the criteria.

In this case, the criteria must reflect a type of characteristic associated with the street, neighborhood or city (defined alternative area) under consideration that makes it more suitable or not to receive a charging point (respectively to maximize or minimize), such as whether the parking is residential or commercial.

The PROMETHEE method can rank the alternative areas in order to support decision makers about specific locations to install charging points. However, this method would provide the best location to implement a facility in a given alternative, but would not take into account that more than one facility has to be implemented. To implement multiple charging points, multiple decisions have to be made. Further, these decisions must take into account previous decisions. Therefore, to install a new charging point in a given area, charging points already installed must be considered.

Previewing that the number of charging points will increase throughout the years, with the adoption of EVs, it is obvious and advisable not to install all charging points in the same "ranked-as-the-best" location. This requires a change to the PROMETHEE method, here introduced, as described below.

B. Dynamic-PROMETHEE

While the result from the PROMETHEE method is a ranking of the alternatives, from the best to the worst, the result from the dynamic-PROMETHEE method (Raposo, 2010) is a set of all decisions made in all alternatives. In this particular case, where a decision is the allocation of a charging point to an alternative, this method is more suited.

Figure 2 presents the dynamic-PROMETHEE detailed methodology, step-by-step, in which each decision is made according to the alternative ranking given by PROMETHEE II. The new approach is taking the previous decision(s) as input for the next decision process.

In order to initialize the algorithm, a complete set of data must be defined. The evaluation criteria, the preference function parameters and the weights are the same as the data required for the PROMETHEE method. However, this approach requires that at least one criterion g_i^d, named dynamic criterion, translates the decisions made and will change its values as these are made.

$$G^d = \left\{g_1^d(.), \qquad g_2^d(.), \ldots, g_m^d(.)\right\} \tag{14}$$

For this specific case, the dynamic criterion is the number of existent charging points in each alternative (or area). As the charging points are allocated to an alternative, this criterion is updated accordingly. This dynamic criterion is evaluated as any other criterion and therefore has a weight of relative importance associated to it and a preference function. The weights are given in respect with formula 10. The preference function parameters of this dynamic criterion can be updated from iteration to iteration if there are modifications in the thresholds of indifference or strict preference.

In order to make the method more robust and modular and because in most real problems the alternatives are not independent from each other, meaning that choosing one can affect other alternatives with different levels of influence, the concept of coalescence matrix is also introduced. The coalescence matrix translates the influence of a decision in one alternative, has on other alternatives. In this case, when a charging point is allocated to a given alternative, this may influence other neighbor alternatives (city areas).

The influence that a decision in alternative a_i has on another alternative a_j represented by $c(a_i, a_j)$, is called the degree of influence of alternative i on alternative j, and is represented as follows:

$$C = \begin{bmatrix} 1 & c(a_1, a_2) & \ldots & c(a_1, a_n) \\ c(a_2, a_1) & 1 & \ldots & c(a_n, a_3) \\ \ldots & \ldots & \ldots & \ldots \\ c(a_n, a_1) & c(a_n, a_2) & \ldots & 1 \end{bmatrix} \tag{15}$$

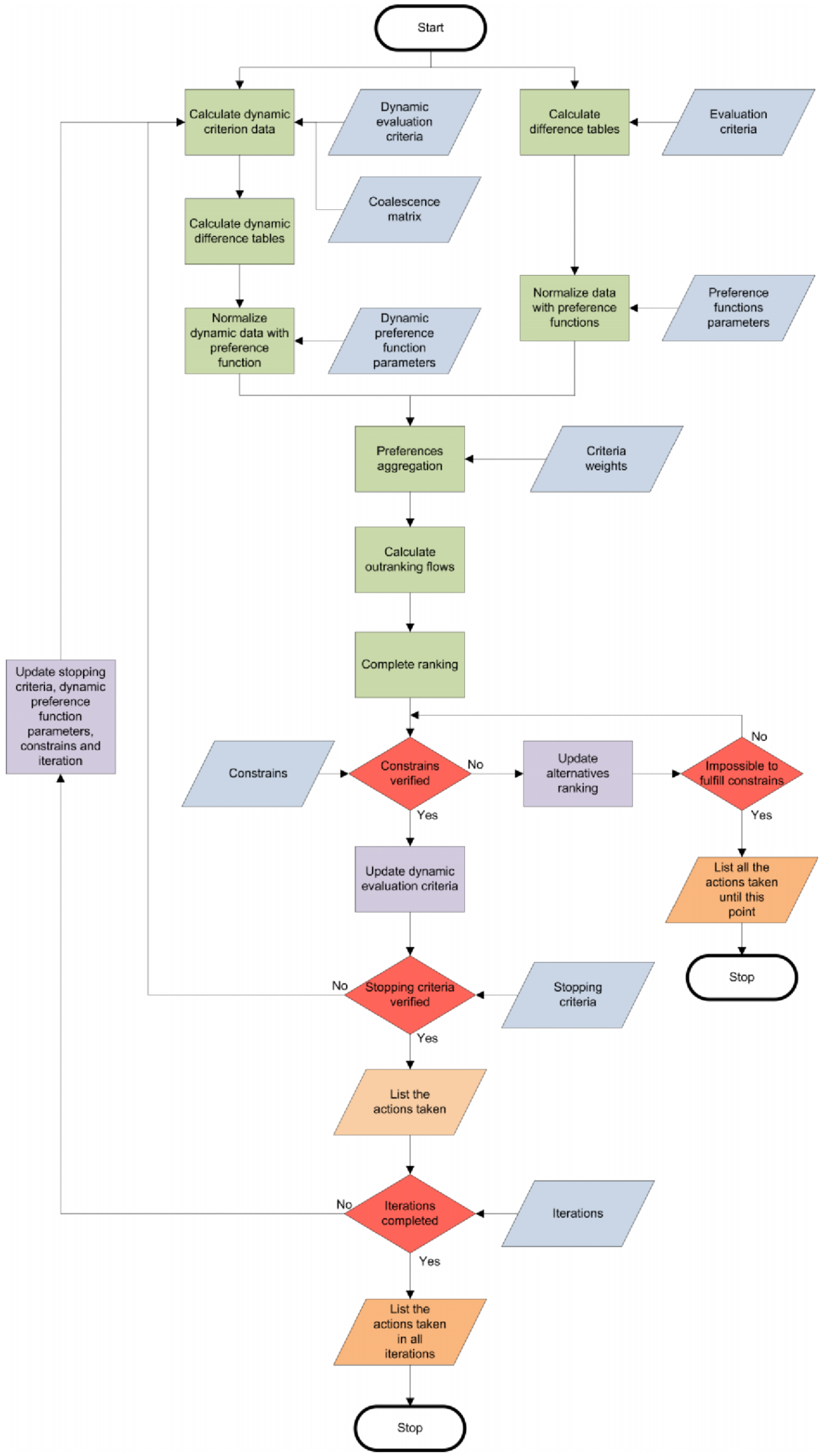

FIG. 2. **Dynamic-PROMETHEE**.

The values of $c(a_i, a_j)$ in this matrix are predetermined by the decision maker and are therefore input data needed for initializing the process (if in use).

The effect of the coalescence matrix is included in the process together with the dynamic criterion, as follows:

$$\left[g'^{d}_{j}(a_i)\right] = C \times \left[g^{d}_{j}(a_i)\right] \tag{16}$$

This transformed dynamic criterion g'^{d}_{j} is considered in the decision process, meaning that all the charging points allocated to the alternatives and the respective influence in others are considered.

The stopping criteria concerns the problem dimension. It is a set of stopping criterion that respects the number of decisions to be done at each iteration t. It may be a fixed number V or dependent $V(t)$ on interactions, considering the decisions $D(a_i,t)$ made at each iteration and can be represented as follows.

$$\sum_{i=1}^{n} D(a_i,t) \le V(t) \tag{17}$$

Constrains Q are related to the alternatives and iterations. They outline the possible decisions that can be made in that alternative and iteration, determining the universe of possible solutions and can be represented as follows:

$$D(a_i,t) \le Q(a_i,t) \tag{18}$$

This will translate in this case, the maximum number of charging points that can be installed in a given alternative area.

III. ANGRA DO HEROÍSMO CASE STUDY

The dynamic-PROMETHEE methodology was applied using Angra do Heroísmo city center data to model the problem, in order to evaluate its performance to design optimized EV charging networks.

A. Alternatives

In order to implement the methodology, the first thing needed is to set and clearly define the alternatives. Due to the particularities of this case, the set of alternatives considered was chosen considering data availability. The problem was modelled using data provided by a private company and by the municipality, regarding the city center division in parking areas and data related to parking lots, implicitly determining the alternative areas to be evaluated. Figure 3 illustrates the seventeen alternatives (areas) considered for this problem.

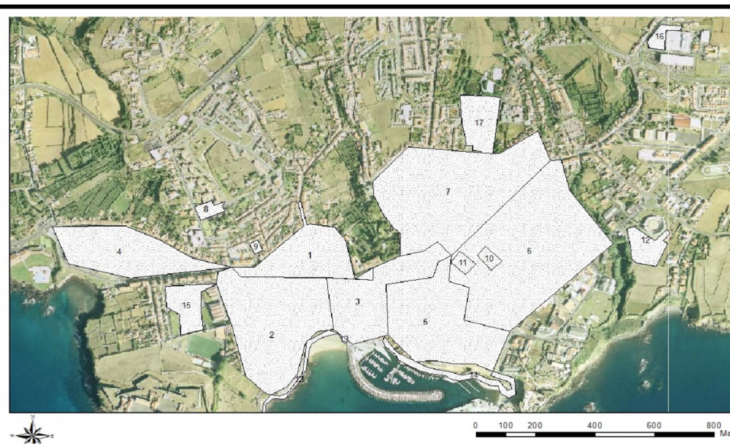

FIG. 3. **Angra do Heroísmo parking areas**.

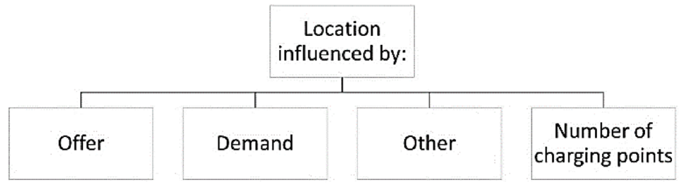

FIG. 4. **Criteria's categories**.

Alternative areas A to G, include paid parking in the streets (with high tariffs) and the Tribunal Parking has a reduced parking tariff. All the remaining areas are free of charge.

B. Criteria

The considered criteria for this task was divided into four categories: criteria related to offer, criteria related to demand, other relevant criteria and the dynamic evaluation criteria (number of existent charging points). This is represented graphically in figure 4.

Table I presents the considered criteria and values.

Criteria related to offer translates the parking availability in terms of parking spaces in the considered alternatives. Since the intention of this study is to separately consider the parking on the public streets and parking lots, two separated criteria are introduced. These define the dimension of the considered alternative areas in terms of number of parking spaces. Thus, the larger the area in terms of parking spaces, the more probable is to have EVs parked in the future. These criteria must then be maximized, meaning that larger areas are preferable.

Criteria related to demand translates indicatively the parking demand pressure in each considered alternative. Nevertheless, the available data does not consider all alternatives in a criterion. So, three criteria must be introduced. The number of cars parked during the daily and night period concerns only the parking lots (alternatives 8 to 17) and the number of registered residents (that can be considered parking during the night) regarding only the public thoroughfare areas (alternatives 1 to 7). Since the numbers are not related, these cannot be aggregated into a single criterion.

Since EV batteries will need at least three hours to charge 80% of the battery, locations where EV users leave their vehicles for a significant period of time (one to three hours at least) are preferable, such as residential public parking during the night. These also include restaurants, theatres, shopping malls, governmental facilities, hotels, amusement and public parks, sports and art venues among others as suggested by Electric Transportation Engineering Corporation (2009).

Only one criterion is considered in the category of other relevant criteria. The area characterization translates numerically, a preference for installing charging points in certain areas. This information was given by stakeholders and decision makers in this matter (namely the municipality and electrical utility representatives), indicating the "preference" to install charging points in alternatives 13 and 14, the parking lot near the marina and the parking lot near the nautical club. To numerically translate this, it is created a criterion that gives the value 2 to these two alternatives and 1 to all others that, with the objective to be maximized, will indicate the preference desired by the stakeholders.

The dynamic evaluation criterion is directly the number of charging stations in each alternative area. This criterion is implicit for this model and will have an initial value of 0 for all alternatives, since there aren't any charging points installed yet, being updated during the process, as charging points are allocated to the alternative areas. This is also the final objective of the study, being the output result.

For this analysis electrical power constraints or availability are not considered. At the time of this work, there was no available data regarding that. It is also assumed that users can always arrive at their destination with one EV battery charge since Angra do Heroísmo is a city in an island with 29 km length and 18 km width and a perimeter of 90 km. Given that the majority of EV models in the market have autonomies tendentially over 160 km and given the orographic profile of Terceira Island, anyone could arrive to its destiny on daily trips with one fully charged battery.

TABLE I. **Criteria used for Angra do Heroísmo**.

	Criteria	Parking offer on the public thoroughfare g_1	Parking offer in parking lots g_2	Cars parked during the day g_3	Cars parked during the night g_4	Registered residents g_5	Area charac-terization g_6	Number of charging points g^d
	Objective	Maximize	Maximize	Maximize	Maximize	Maximize	Maximize	Minimize
1	**Parking area A**	273	0	0	0	212	1	0
2	**Parking area B**	510	0	0	0	414	1	0
3	**Parking area C**	265	0	0	0	195	1	0
4	**Parking area D**	378	0	0	0	402	1	0
5	**Parking area E**	360	0	0	0	399	1	0
6	**Parking area F**	410	0	0	0	197	1	0
7	**Parking area G**	337	0	0	0	451	1	0
8	**Santa Luzia Parking**	0	80	80	20	0	1	0
9	**Queimada Parking**	0	32	32	10	0	1	0
10	**Tribunal Parking**	0	80	80	15	0	1	0
11	**Guarita Parking**	0	63	63	10	0	1	0
12	**Praça de touros Parking**	0	340	340	0	0	1	0
13	**Clube Náutico Parking**	0	80	60	0	0	2	0
14	**Marina Parking**	0	80	60	0	0	2	0
15	**Bailão Parking**	0	389	389	15	0	1	0
16	**Shopping mall Parking**	0	400	80	0	0	1	0
17	**Hospital Parking**	0	200	200	50	0	1	0

C. Stopping criteria

A study conducted by Roland Berger consultants (MOBI.E, 2009) was considered in order to have an estimate for the number of electric vehicles in Angra do Heroísmo. This city adoption curve for EVs was extrapolated from the adoption curve for Portugal, establishing a proportional relation between the number of vehicles in Portugal and the number of vehicles in Angra do Heroísmo. This ratio is considered to remain constant in time (0,34%) since population is not considered as a variable. Nevertheless, the estimates for the number of EVs given here (or any other data in terms of numbers) are not relevant to validate the methodology neither is the objective of this article to give these forecasts or evaluate the quality of the data in numbers.

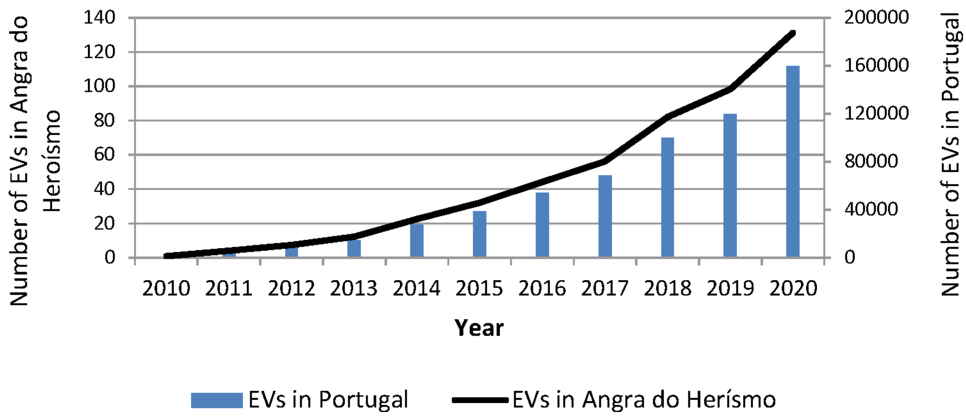

FIG. 5. **EV Demand Curve**.

Having this said, the estimated number of EVs in Angra do Heroísmo will evolve from 32 in 2015 up to 131, in 2020 (Figure 5).

To relate EVs number with charging stations, the concept of service degree is introduced. This indicates the number of EVs that can charge with the same charging station. It is also considered that each charging station is constituted by two charging points, based on the actual charging points being installed in Portugal. From discussions with some stakeholders, it is predicted that there will be a relation of two EVs per charging point and that this relation will evolve in the future to five EVs per charging point. This is translated into a service degree of 0,5 for the first year linearly decreasing to 0,3 in 2020 (Figure 6).

Once more, the objective of this article is not to give accurate data which is open to discussion, but only give indicative and understandable data to be able to apply the algorithm.

The number of charging points needed for each year is determined relating the estimate number of EVs with the service degree for the respective year. This will serve as the stopping criterion, guarantying that the number of charging points to install are the ones needed.

Additionally, other constrains are introduced to limit the number of charging stations that can be allocated to a given area. Since there are two types of areas (street areas and parking lots), two constraints are introduced, namely the number of charging stations in streets and in parking lots. Charging stations in streets cannot be superior to 5% of the parking spaces in those areas, whereas the charging stations in a parking lot cannot be superior to 10%.

D. Coalescence matrix

When installing a charging station in a given area, this will influence at least the adjacent area and even more if the charging point is installed near the limit of that area. Also, since the study

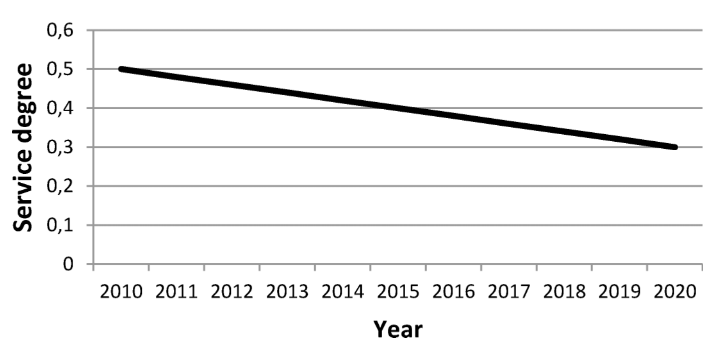

FIG. 6. **Service degree (Angra do Heroísmo)**.

TABLE II. **Coalescence matrix for Angra do Heroísmo**.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
1	1	0,2	0,2	0,05	0	0	0	0,1	0,1	0	0	0	0	0	0,05	0	0
2	0,2	1	0,2	0,05	0	0	0	0	0	0	0	0	0,3	0	0,05	0	0
3	0,2	0,2	1	0	0,2	0	0,1	0	0	0	0	0	0,2	0,05	0	0	0
4	0,05	0,05	0	1	0	0	0	0,1	0,1	0	0	0	0	0	0,2	0	0
5	0	0	0,2	0	1	0,2	0,1	0	0,1	0,1	0	0	0,05	0,3	0	0	0
6	0	0	0	0	0,2	1	0,1	0	0	0,3	0,3	0,1	0	0	0	0	0
7	0	0	0,1	0	0,1	0,1	1	0	0	0,1	0,1	0	0	0	0	0	0
8	0,1	0	0	0,1	0	0	0	1	0,1	0	0	0	0	0	0	0	0
9	0,1	0	0	0,1	0,1	0	0	0,1	1	0	0	0	0	0	0	0	0
10	0	0	0	0	0,1	0,3	0,1	0	0	1	0,1	0	0	0	0	0	0
11	0	0	0	0	0	0,3	0,1	0	0	0,1	1	0	0	0	0	0	0
12	0	0	0	0	0	0,1	0	0	0	0	0	1	0	0	0	0	0
13	0	0,3	0,2	0	0,05	0	0	0	0	0	0	0	1	0,1	0	0	0
14	0	0	0,05	0	0,3	0	0	0	0	0	0	0	0,1	1	0	0	0
15	0,05	0,05	0	0,2	0	0	0	0	0	0	0	0	0	0	1	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

area is small, the influence in the surrounding areas is different. Charging stations allocated in the parking lot alternatives will influence the number of charging stations in the street areas and vice versa.

Table II shows the coalescence matrix used for this study. The values in this table were decided with the contribution of the stakeholders.

E. Sensitivity analysis

The sensitivity analysis considers three different policies, with different weights and different criteria, in order to produce different scenarios. Thus, four scenarios were created and results evaluated, being the first scenario related with the first policy, the second scenario with the second policy and the last two scenarios related with the third policy.

Scenario 1– No preferences for parking areas

Scenario one translates policy option number one that considers no preference for the parking areas, being based strictly on the parking offer and demand and the urban structure.

Scenario 2– Preferences for the Marina Parking

Scenario two translates policy option number two and apart from scenario one foresees stimulation policies for EV users to use areas with low demand in parking in order to optimize parking. Therefore it gives preference to the Marine parking.

Scenario 3– Transference of parking demand from the areas Bailão and Praça de Touros to public thoroughfare in central areas

Commuting parking (Parque do Bailão and Praça de Touros) located outside Angra do Heroísmo urban center are larger, being served by a bus inter-parks service, free of charge, with high demand from users that work in central areas, in order to avoid parking fees in the center. These two commuting parks are part of the present strategy of the municipality to avoid excess traffic and parking within central city limits, thus reducing noise and air pollution in those areas. However, as ICEV are substituted by EVs, it will be possible to address this matter from another point of view, since EVs do not pose problems of noise or tailpipe emissions (although the traffic problem may remain). Therefore, scenarios three and four consider transference of parking demand from outside of the urban center to the urban center, as a hypothetical result of EV users being exempted of fees when parking in the urban center.

Hence scenario three, which translates policy option number three, considers parking change from Bailão and Praça de Touros to public streets in central areas. This scenario considers distribution of parking areas (A, B, C, D, E, F and G) with similar weights for offer and demand. No correction factor was introduced for the shopping mall parking area, despite being far from the center, since Hospital parking demand may overcome this problem given the small distance between them.

Scenario 4– Same as scenario 3, but considering higher preference for parking in central area A and lower preference for parking in the shopping mall

Scenario four is still associated with policy number three, but it is created to balance the large number of parking spots and small time parking in the fringe parking of the shopping mall. Additionally, it considers higher preference to parking in central area A and lower preference to parking in the shopping mall. This last scenario considers that users, who nowadays use Bailão and Praça de Touros (outside the urban center) parking will use urban street areas in the future, distributed according to parking spots percentages of areas A, B, C, D, E, F and G.

Also, the area characterization criterion was used to distinguish preferences given to different areas. The objective was to stimulate parking in the urban center (Area A), giving more weigh to this area than to others. Since the shopping mall parking is far from center, less preference is assigned to it in order to balance the large number of parking spots and small time parking. This was considered to avoid the "absorption" of charging stations from other advisable areas.

IV. RESULTS

The dynamic-PROMETHEE methodology was applied to obtain an "optimized" EV charging network in Angra do Heroísmo, considering that these would be located on existing parking spaces.

Considering Angra do Heroísmo EV demand curve (Figure 5) and the service degree (Figure 6), it is estimated for 2015 that seven charging points should be deployed. Each with two charging plugs included, up to a number of twenty charging points in 2020.

For scenario one (policy number one) parking area F and Nautical Club will never have charging stations and areas which currently have high demand will have more charging stations (Table III).

For scenario two (Table IV), EV users are stimulated to use the Marine parking space (outside the urban centre, but nearby), alleviating parking in central areas. Area B should have two charging points already in 2015, as well as Area G, Praça de Touros, Marine, Bailão, Shopping Mall and Hospital parks. Area C, Queimada Parking, Guarita and the Nautical Club are not planned to have any charging points up to 2020.

TABLE III. **Scenario one - charging points assigned to each parking area**.

Year		2015	2016	2017	2018	2019	2020
1	A (urban centre)	0	0	2	2	2	2
2	B (urban centre)	2	2	2	2	2	4
3	C (urban centre)	0	0	0	0	2	2
4	D (urban centre)	0	2	2	2	2	2
5	E (urban centre)	2	2	2	2	2	2
6	F (urban centre)	0	0	0	0	0	0
7	G (urban centre)	2	2	2	2	2	2
8	Santa luzia (urban centre)	0	2	2	2	2	2
9	Queimada (urban centre)	0	0	0	0	0	2
10	Court (urban centre)	0	0	2	2	2	2
11	Guarita (urban centre)	0	0	0	0	2	2
12	Praça de Touros	2	2	2	4	4	4
13	Nautical Club Parking	0	0	0	0	0	0
14	Marine Parking	0	0	0	0	0	2
15	Bailão Parking	2	2	2	4	4	4
16	Shopping Mall Parking	2	2	2	2	2	4
17	Hospital Parking	2	2	2	4	4	4
	Total	14	18	22	28	32	40

TABLE IV. **Scenario two - charging points assigned to each parking area**.

Year		2015	2016	2017	2018	2019	2020
1	A (urban centre)	0	0	0	2	2	2
2	B (urban centre)	2	2	2	2	2	4
3	C (urban centre)	0	0	0	0	0	0
4	D (urban centre)	0	2	2	2	2	2
5	E (urban centre)	0	0	0	2	2	2
6	F (urban centre)	0	2	2	2	2	2
7	G (urban centre)	2	2	2	2	2	2
8	Santa luzia (urban centre)	0	0	2	2	2	2
9	Queimada (urban centre)	0	0	0	0	0	0
10	Court (urban centre)	0	0	0	0	0	2
11	Guarita (urban centre)	0	0	0	0	0	0
12	Praça de Touros	2	2	2	2	4	4
13	Nautical Club Parking	0	0	0	0	0	0
14	Marine Parking	2	2	4	4	4	6
15	Bailão Parking	2	2	2	2	4	4
16	Shopping Mall Parking	2	2	2	2	2	4
17	Hospital Parking	2	2	2	4	4	4
	Total	14	18	22	28	32	40

TABLE V. **Scenario three - charging points assigned to each parking area**.

Year		2015	2016	2017	2018	2019	2020
1	A (urban centre)	0	0	2	2	2	2
2	B (urban centre)	2	2	2	2	4	4
3	C (urban centre)	0	0	0	0	0	0
4	D (urban centre)	2	2	2	2	2	2
5	E (urban centre)	2	2	2	2	2	2
6	F (urban centre)	0	0	0	0	0	0
7	G (urban centre)	2	2	2	2	2	4
8	Santa luzia (urban centre)	0	2	2	2	2	2
9	Queimada (urban centre)	0	0	0	0	0	2
10	Court (urban centre)	0	0	2	2	2	2
11	Guarita (urban centre)	0	0	0	2	2	2
12	Praça de Touros	2	2	2	2	2	4
13	Nautical Club Parking	0	0	0	0	0	0
14	Marine Parking	0	0	0	2	2	2
15	Bailão Parking	0	2	2	2	2	4
16	Shopping Mall Parking	2	2	2	2	4	4
17	Hospital Parking	2	2	2	4	4	4
	Total	14	18	22	28	32	40

The charging points increase over the considered timeline mainly in the area B, in Praça de Touros, Marine Parking, Shopping mall and Hospital.

Table V presents results for scenario three. In this scenario charging points are mainly assigned to the central areas. Areas B, D, E, and G, and also in Praça de Touros, Shopping Mall and Hospital are put up to have charging points installed starting 2015.

Changes will occur during the following years, mainly at area A which will have two charging points from 2017. Area B should have more two charging points in 2019. Area G should have four charging points by 2020, as well as Praça de Touros and Bailão. The Shopping Mall will increase charging points to four in 2019 and Hospital will have four charging points by 2018.

TABLE VI. **Scenario four - charging points assigned to each parking area**.

Year		2015	2016	2017	2018	2019	2020
1	A (urban centre)	2	2	2	2	4	4
2	B (urban centre)	2	2	2	2	2	2
3	C (urban centre)	0	0	0	0	0	0
4	D (urban centre)	2	2	2	2	2	2
5	E (urban centre)	2	2	2	2	2	2
6	F (urban centre)	0	0	0	0	0	0
7	G (urban centre)	2	2	2	2	2	4
8	Santa luzia (urban centre)	0	2	2	2	2	2
9	Queimada (urban centre)	0	0	0	0	0	2
10	Court (urban centre)	0	0	2	2	2	2
11	Guarita (urban centre)	0	0	0	2	2	2
12	Praça de Touros	2	2	2	2	2	4
13	Nautical Club Parking	0	0	0	0	2	2
14	Marine Parking	0	0	0	2	2	2
15	Bailão Parking	0	2	2	2	2	2
16	Shopping Mall Parking	0	0	2	2	2	2
17	Hospital Parking	2	2	2	4	4	6
	Total	14	18	22	28	32	40

Scenario four differs from scenario three only by the fact that a higher preference is given to parking in the urban center (Area A) and lower preference is given to parking in the shopping mall, to correct the weight posed by the large number of parking spaces used by the shopping mall users and hospital employees and users.

If this procedure would not be done, charging stations would be assigned preferably to the hospital and to the shopping mall, being these areas relatively far from the center (Table VI). Being far from the center, users hardly would prefer to leave their cars there and make way to their work (or any other destiny at the city center) by walking. Here, it can be seen that preferences of EV users should be considered when designing policies and consequently designing input data to create scenarios.

Scenario four suggests that charging points should be allocated in 2015 mainly in the urban center (Areas A, B, D, E, G) and at the Hospital. It also suggests that, in time, all areas except Area C and F should have charging points, being urban areas A and G and areas outside the urban center (Praça de Touros and Hospital) the ones with more charging points in 2020.

V. DISCUSSION AND CONCLUSIONS

The main objective of this work was to test this methodology for solving the problem associated with the planning of the number and location of charging points for EVs to deploy in a given area throughout a period of predefined time. This objective is achieved with the proposed methodology, dynamic-PROMETHEE.

The case study presented in this work gives a clear view of the versatility of the methodology in terms of scale of area considered for the study and in modelling possible policies and scenarios. It is possible to consider a study area as large as a country or as small as a neighbourhood, providing that there is data that complies with the method's requirements (as in any other decision aid methodology). In fact, data collection and definition (such has criteria weights) revealed to be an important step, being sometimes not only difficult to find all the data available but also to be able to have the data formatted according to the requirements. In this process, stakeholders and decision makers have a pivotal role. Nevertheless, this was expected since this is a common issue in any multi-criteria decision aid methodology. The data subjectivity, precision and interpretation are matters that are always present in such methodologies, and this one is no different.

Even so, from the sensitivity analysis we can conclude that the dynamic-PROMETHEE methodology behaves in a predictable manner and can easily translate the evaluation intentions of the stakeholders and decision makers. Apart from the scenarios differences, there are tendencies that show and can lead the way to better policies and decisions, such as to have 7 charging points by 2015 in Angra do Heroísmo, increasing to 9 in 2016, 11 in 2017, 14 in 2018, 16 in 2019 and 20 in 2020. Of course these results are directly linked to the data considered and one can argue that it does not translate the reality. But that would be a different discussion. From the model point of view, the distribution of charging points in the considered areas are different according to the set scenarios, as expected.

Scenario one, which considered only the current offer and demand for parking areas, assigned more or less charging points according to current high or low demand for the parking areas, respectively.

Scenario two considered an incentive for EV users to use the Marine parking, currently with low demand, in order to relieve parking in the urban center. For this scenario, the model suggested to site charging stations prioritizing the Marine parking space and adjusting all the remaining offer of charging stations accordingly, indeed lowering charging stations sited at the urban center.

Scenario three showed some deviations from the intended policy, since the hospital and the shopping mall parking areas have a high demand for costumers and workers, diminishing the effect of the transferred charging stations from other areas to the urban center, by "attracting" charging stations to them. In this case, results did not comply with the intended policy, leading to a reevaluation of this. Therefore, scenario four was created to overcome this problem. The introduction of lower weights to the hospital and to the shopping mall, which is far from the center and would probably not be a real option for the users, better translated the policy intention.

Scenario four presents more consistent results with the policy goals, by transferring charging stations to the urban center and adjusting the remaining charging stations accordingly. This shows the weight definition importance to attain satisfactory results with this methodology, as predicted. It is advisable in a real application study using these type of methodologies to perform a sensitivity analysis to the weight so that decision makers can better understand the implications of their definitions.

As an overall conclusion, it is here demonstrated that dynamic-PROMETHEE is an adequate methodology to perform an analysis concerning the distribution of charging points for EVs in a given area such as a city. However it is not limited to it. The openness and the dynamic features of the dynamic-PROMETHE methodology give it unique characteristics that are much useful in other problems.

One of the main characteristics of this methodology is the "memory" of past decisions. This meaning that decisions being taken at a certain iteration, will always take into consideration previous decisions, through the inclusion of the dynamic criteria. This is very useful for example, to model the distribution of any service in an area, such as the distribution of a health service in a country. This characteristic can also be very useful for example, when deciding the sequence of treatments to perform in a patient. If there are several sequential treatments that should be performed in a patient and these are influenced by previous treatments, applying a methodology like dynamic-PROMETHEE can give the complete picture of the sequence. These are only a couple of examples of possible applications for the dynamic-PROMETHEE methodology that prove its value in the field of decision aid methodologies.

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Al-Rashdan, D., Al-Kloub, B., Dean, A., and Al-Shemmeri, T., "Environmental impact assessment and ranking the environmental projects in Jordan," European Journal of Operational Research. **118**, 30-45 (1998).

Babic, Z. and Plazibat, N., "Ranking of enterprises based on multicriterial analysis," International Journal of Production Economics **56-57**, 29-35 (1998).

Behzadian, M., Kazemzadeh, R.B., Albadvi, A., and Aghdasi, M., "PROMETHEE: A comprehensive literature review on methodologies and applications," European Journal of Operational Research, 200(Decision Support) **200**, 198–215 (2009).

Brans, J.P. and Mareschal, B., "Promethee Methods," in *Multiple Criteria Decision Analysis: State of the Art Surveys*, edited by Greco Salvatore (Springer, New York, 2005), pp. 163-86.

Brans, J.P., Vincke, P., and Mareschal, B., "How to select and how to rank projects: The Promethee method," European Journal of Operational Research. **24**, 228-238 (1986).

Camus, C., Baptista, P., Silva, C., and Farias, T., "Strategic Marketing Plan for Battery Electric Vehicles. The Portuguese Case," in *International Advanced Mobility Forum - Geneva International Motor Show*, *Geneva*, *2010* (2010).

Chan, C.C., "The state of the art of electric and hybrid vehicles," Proceedings of the IEEE **90**, 247–275 (2002).

Chapman, L., "Transport and climate change: a review," Journal of Transport Geography. **15**, 354-67 (2007).

Chen, D., Khan, M., and Kockelman, K., "The Electric Vehicle Charging Station Location Problem: A Parking-Based Assignment Method for Seattle," http://www.ce.utexas.edu/prof/kockelman/public_html/TRB13EVparking.pdf [accessed in 2014] (2013).

Drezner, Z., "Dynamic facility location: The progressive p-median problem," Location science. **3**, 1–7 (1995).

Electric Transportation Engineering Corporation, *Electric Vehicle Charging Infrastructure Deployment Guidelines British Columbia* (British Columbia Hydro and Power Authority, 2009).

Elevli, B. and Demirci, A., "Multicriteria choice of ore transport system for an underground mine: Application of PROMETHEE methods," Journal of The South African Institute of Mining and Metallurgy. **104**, 251-56 (2004).

Fernández, G. M. and Martin, M. A., "La Decisión Multicriterio en la elección del emplazamiento de un Parque. Valencia," ASEPUMA 244-255 (1999).

Frade, I., Ribeiro, A., Goncalves, G., and Antunes, A.P., "Optimal Location of Charging Stations for Electric Vehicles in a Neighborhood in Lisbon, Portugal," Transportation Research Record: Journal of the Transportation Research Board. **2252**, 91-98 (2011).

Gartner, J. and Wheelock, C., "Electric Vehicles on the Grid," *Research Report* (Pikeresearch LLC, 2009).

Gavranović, H., Barut, A., Ertekc, G, Yüzbaşıoğluc, OB, Pekpostalcıc, O, and Tombuşd, O., "Optimizing the Electric Charge Station Network of EŞARJ," in *2nd International Conference on Information Technology and Quantitative Management, ITQM 2014. Procedia Computer Science*, edited by Yong Shi, Alexander Lepskiy, and Fuad Aleskerov (2014), Vol. 31, pp. 15–21.

Green, E.H., Skerlos, S.J., and Winebrake, J.J., "Increasing electric vehicle policy efficiency and effectiveness by reducing mainstream market bias," Energy Policy. **65**, 562–566 (2014).

Hahn, P.M. and Krarup, J., "A hospital facility layout problem finally solved," Journal of Intelligent Manufacturing. **12**, 487-96 (2001).

Hanabusa, H. and Horiguchi, R., "A study of the analytical method for the location planning of charging stations for electric vehicles," Knowledge-Based and Intelligent Information and Engineering Systems. 596-605 (2011).

Helmers, E and Marx, P., "Electric cars: technical characteristics and environmental impacts," Environmental Sciences Europe **24**, 14 (2012).

Hokkanen, J. and Salminen, P., "Choosing a solid waste management system using multicriteria decision analysis," European Journal of Operational Research. **98**, 19–36 (1997).

James, A., "Presentation to the Governor's Alternative Fuel Infrastructure Working Group," Office of Innovative Partnerships. Oregon Department of Transportation (2009). www.oregon.gov/odot/hwy/oipp/innovative.shtml [Accessed in 2010].

Kempton, W. and Letendre, S. E., "Electric vehicles as a new power source for electric utilities," Transportation Research Part D: Transport and Environment. **2**, 157–175 (1997).

Kempton, W. and Tomić, J., "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue," Journal of Power Sources. **44**, 268–279 (2005).

Kim, J. and Rahimi, M., "Future energy loads for a large-scale adoption of electric vehicles in the city of Los Angeles: Impacts on greenhouse gas (GHG) emissions," Energy Policy. **73**, 620-30 (2014).

Mak, H-I, Rong, Y., and Shen, Z-J. M., "Infrastructure Planning for Electric Vehicles with Battery Swapping," Management Sciences. **59**, 1557–75 (2013).

MOBI.E, Portuguese Electric Mobility Program". Lisbon, 2009. October 2. Inteli, 2009. MOBI.E - Mobilidade Eléctrica. http://www.mobi-e.pt [Accessed in 2010] (2009).

Owen, S.H. and Daskin, M.S., "Strategic facility location: A review," European Journal of Operational Research. **111**, 423-47 (1998).

Pina, A., Baptista, P., Silva, C., and Ferrão, P., "Energy reduction potential from the shift to electric vehicles: The Flores island case study," Energy Policy. **67**, 37-47 (2014).

Queiruga, D., Walther, G., González-Benito, J., and Spengler, T.S., "Evaluation of sites for the location of WEEE recycling plants in Spain," Waste Management. **28**, 181-90 (2008).

Raposo, João., "Location of Charging Points for Electrical Vehicles using Decision Analysis: Lisbon and Santarém case studies," Lisbon – Técnico Lisboa – Lisbon University. (2010).

Sousa, J.M.C. and Kaymak, U., *Fuzzy Decision Making in Modeling and Control* (World Scientific Publishing Co. Pte.Ltd, Singapore, 2002).

Sovacool, B.K. and Hirsh, R.F., "Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition," Energy Policy. **37**, 1095–1103 (2009).

van den Bossche, P., Maggetto, G., and Van Mierlo, J., *The Brussels Capital Region: A Case Study for Electric Vehicle Infrastructure DeploymentBrussels: Vrije Universiteit Brussel* (2003).

Verdantix, "Case Study: Better Place electric vehicle system," www.verdantix.com [Accessed in 2010] (2009).

Vincke, P., *Multicriteria Decision-aid* (John Wiley & Sons, Ltd, Bruxelles, 1992).

Wang, Y.-W. and Lin, C.-C., "Locating road-vehicle refueling stations," Transportation Research Part E. **45**, 821-29 (2009).

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A multi-criteria decision aid methodology to design electric vehicles public charging networks

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